US009689903B2

(12) **United States Patent**
**Sharma et al.**

(10) **Patent No.: US 9,689,903 B2**
(45) **Date of Patent: Jun. 27, 2017**

(54) **APPARATUS AND METHODS FOR MEASURING CURRENT**

(71) Applicant: **Analog Devices, Inc.**, Norwood, MA (US)

(72) Inventors: **Yogesh Jayaraman Sharma**, Santa Clara, CA (US); **Nathan R. Carter**, Santa Clara, CA (US); **Teera Songatikamas**, San Jose, CA (US); **Brendan Cronin**, Reading, MA (US)

(73) Assignee: **Analog Devices, Inc.**, Norwood, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/457,560**

(22) Filed: **Aug. 12, 2014**

(65) **Prior Publication Data**

US 2016/0047846 A1 Feb. 18, 2016

(51) **Int. Cl.**

| | |
|---|---|
| ***G01R 33/02*** | (2006.01) |
| ***G01R 15/20*** | (2006.01) |
| ***G01R 33/09*** | (2006.01) |

(52) **U.S. Cl.**
CPC ......... ***G01R 15/207*** (2013.01); ***G01R 15/202*** (2013.01); ***G01R 15/205*** (2013.01); ***G01R 33/096*** (2013.01)

(58) **Field of Classification Search**
CPC .. G01R 33/096; G01R 15/207; G01R 15/202; G01R 15/205

(Continued)

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,422,566 A * 6/1995 Boenning ............ G01R 15/148 324/117 R
5,473,244 A * 12/1995 Libove ..................... G01R 1/22 324/126

(Continued)

FOREIGN PATENT DOCUMENTS

CH EP 2202527 A1 * 6/2010 ........... G01R 15/202
CN 103487632 A 1/2014

(Continued)

OTHER PUBLICATIONS

Kaine-Krolak, "An Introduction to Infrared Technology: Applications in the Home, Classroom, Workplace, and Beyond . . . ", 1995, trace.wisc.edu.*

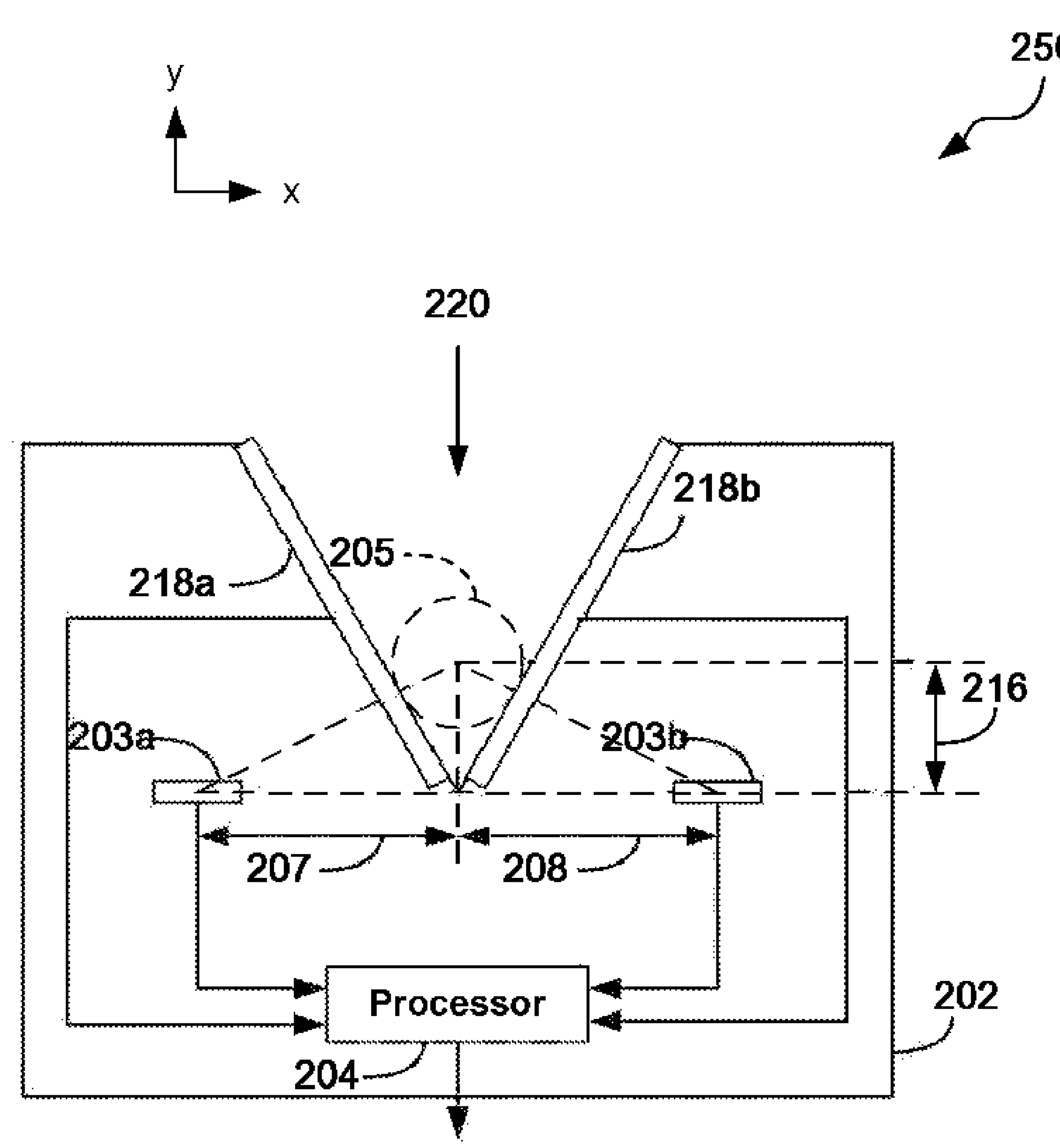
(Continued)

*Primary Examiner* — Patrick Assouad
*Assistant Examiner* — Sean Curtis
(74) *Attorney, Agent, or Firm* — Knobbe, Martens, Olson & Bear, LLP

(57) **ABSTRACT**

In an embodiment, a body of apparatus includes an opening, such as a V-shaped jaw, that deterministically locates a position of a wire in at least one dimension when the wire is placed in the opening. The apparatus also includes a plurality of sensors. At least one differential signal can be generated from signals from magnetic sensors, such as anisotropic magnetoresistance (AMR) sensors, of the plurality of sensors to cancel out common mode interference. An additional sensor of the plurality of sensors provides an output from which the location of the wire in another dimension is determined. The current flowing through the wire can be derived from at least the at least one differential signal and the location of the wire the other dimension.

**25 Claims, 5 Drawing Sheets**



(58) **Field of Classification Search**
USPC ......... 324/249, 207.13, 207.14, 207.22, 219, 324/228, 247, 117 R, 126
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

| | | | | | |
|---|---|---|---|---|---|
| 5,717,326 | A * | 2/1998 | Moriwaki | G01R 15/18 | 324/117 H |
| 5,767,668 | A * | 6/1998 | Durand | G01R 31/2844 | 324/117 R |
| 6,252,389 | B1 * | 6/2001 | Baba | G01R 15/202 | 324/117 H |
| 7,164,263 | B2 * | 1/2007 | Yakymyshyn | G01R 15/207 | 324/117 H |
| 7,719,258 | B2 * | 5/2010 | Chen | G01R 15/202 | 324/117 H |
| 8,400,138 | B2 * | 3/2013 | Cooper | G01R 15/181 | 324/117 R |
| 8,922,194 | B2 * | 12/2014 | Blake | G01R 33/032 | 324/96 |
| 2003/0112006 | A1 * | 6/2003 | Luetzow | G01D 5/145 | 324/207.21 |
| 2008/0077336 | A1 * | 3/2008 | Fernandes | G01R 15/142 | 702/57 |
| 2011/0248711 | A1 * | 10/2011 | Ausserlechner | G01R 15/207 | 324/251 |
| 2012/0187937 | A1 * | 7/2012 | Blake | G01R 33/032 | 324/96 |
| 2012/0290240 | A1 * | 11/2012 | Fukui | G01R 15/20 | 702/65 |
| 2013/0033260 | A1 * | 2/2013 | Nomura | G01R 15/207 | 324/252 |
| 2013/0106400 | A1 * | 5/2013 | Cheng | G01R 15/20 | 324/117 R |
| 2013/0285825 | A1 * | 10/2013 | Peczalski | G01R 33/07 | 340/664 |
| 2014/0028308 | A1 * | 1/2014 | Ogomi | G01R 33/096 | 324/252 |
| 2014/0347036 | A1 * | 11/2014 | Noh | G01R 15/183 | 324/126 |
| 2015/0016006 | A1 * | 1/2015 | van Vroonhoven | H01F 13/006 | 361/149 |
| 2015/0042320 | A1 * | 2/2015 | Cadugan | G01R 33/06 | 324/207.2 |
| 2015/0316623 | A1 * | 11/2015 | Romero | G01R 33/077 | 324/251 |
| 2015/0331072 | A1 * | 11/2015 | Ogawa | G01R 33/1253 | 324/252 |
| 2015/0338473 | A1 * | 11/2015 | Diaconu | G01R 33/0029 | 324/251 |

FOREIGN PATENT DOCUMENTS

| | | | | | |
|---|---|---|---|---|---|
| EP | 1 037 056 | A1 | | 9/2000 | |
| EP | 1037056 | A1 | * | 9/2000 | |
| EP | 2 202 527 | A1 | | 6/2010 | |
| EP | 2202527 | A1 | * | 6/2010 | |
| JP | 09-308615 | A | * | 12/1997 | G01R 33/02 |
| JP | 09308615 | A | * | 12/1997 | |
| JP | EP 1037056 | A1 | * | 9/2000 | G01R 15/14 |
| JP | 2012-098205 | A | | 5/2012 | |
| PL | WO 2011154157 | A1 | * | 12/2011 | G01R 15/183 |
| WO | WO 2011154157 | A1 | * | 12/2011 | |
| WO | WO 2013/099504 | A1 | | 7/2013 | |

OTHER PUBLICATIONS

Rogowski Coil, Wikipedia Entry, http://en.wikipedia.org/wiki/Rogowski_coil (accessed Nov. 14, 2014), 5 pages.

* cited by examiner

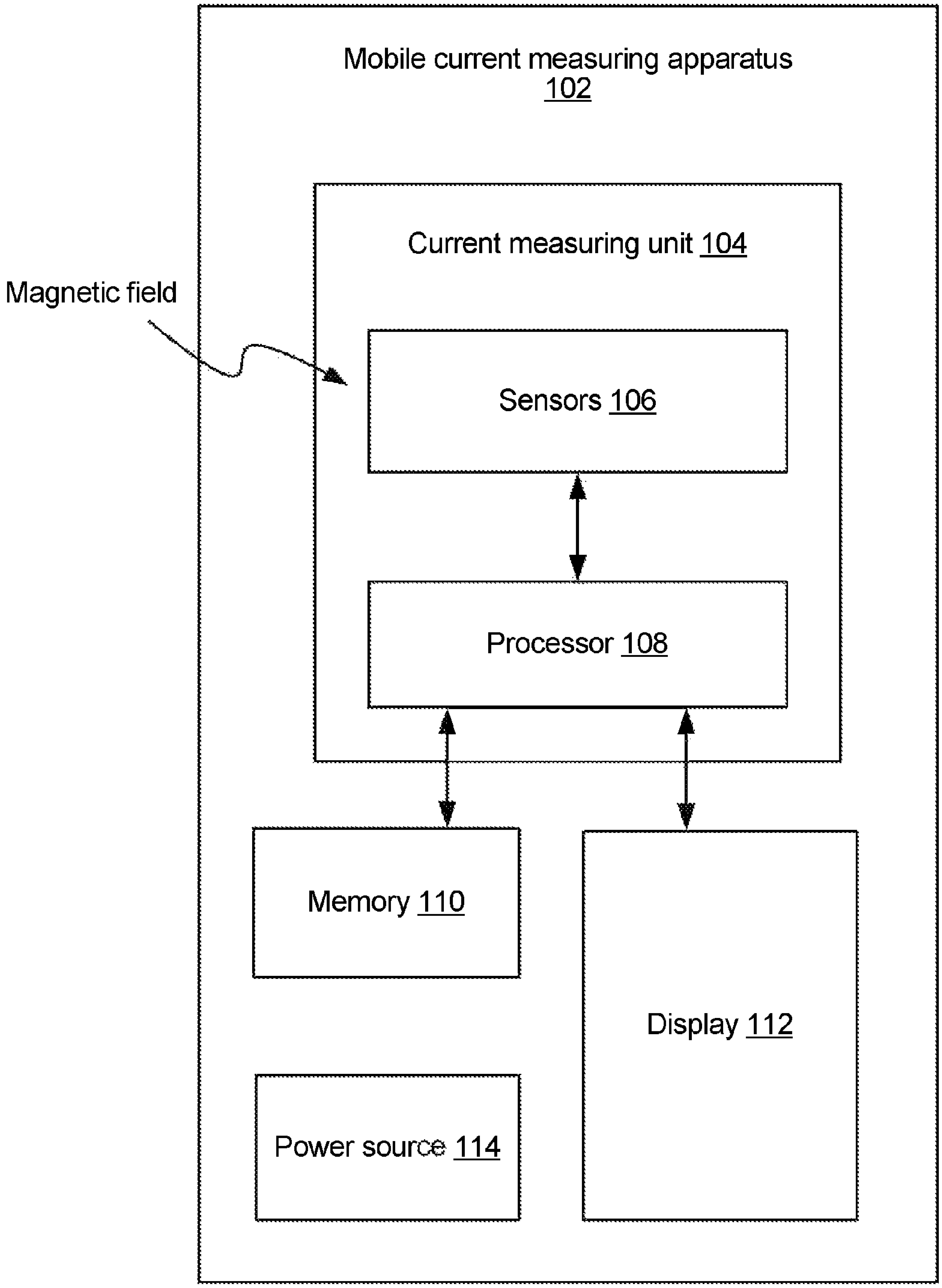

Mobile current measuring apparatus
102
Current measuring unit 104
Magnetic field
Sensors 106
Processor 108
Memory 110
Display 112
Power source 114

FIG. 1

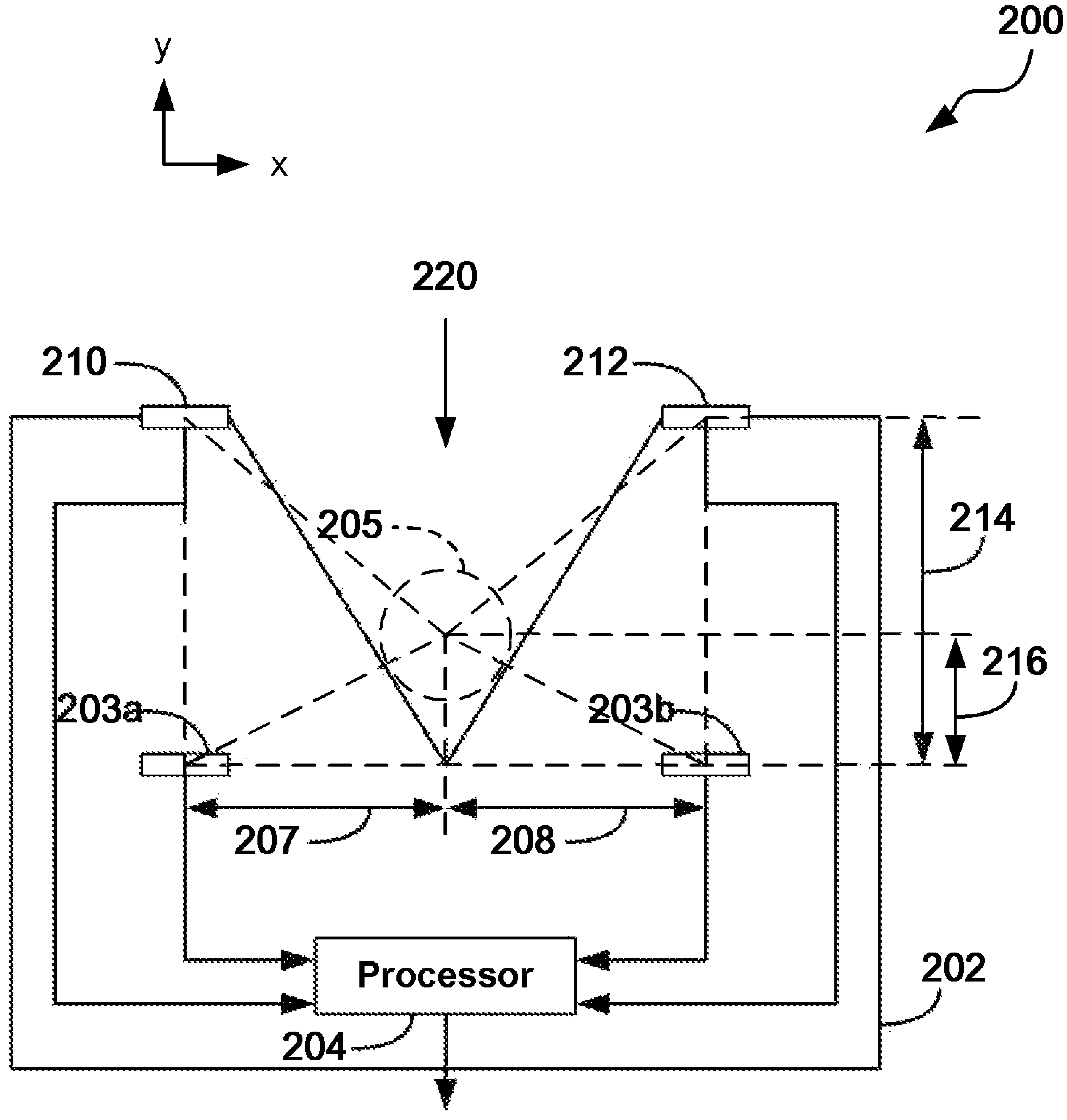

200
y
x
220
210
212
205
214
216
203a
203b
207
208
Processor
202
204

FIG. 2A

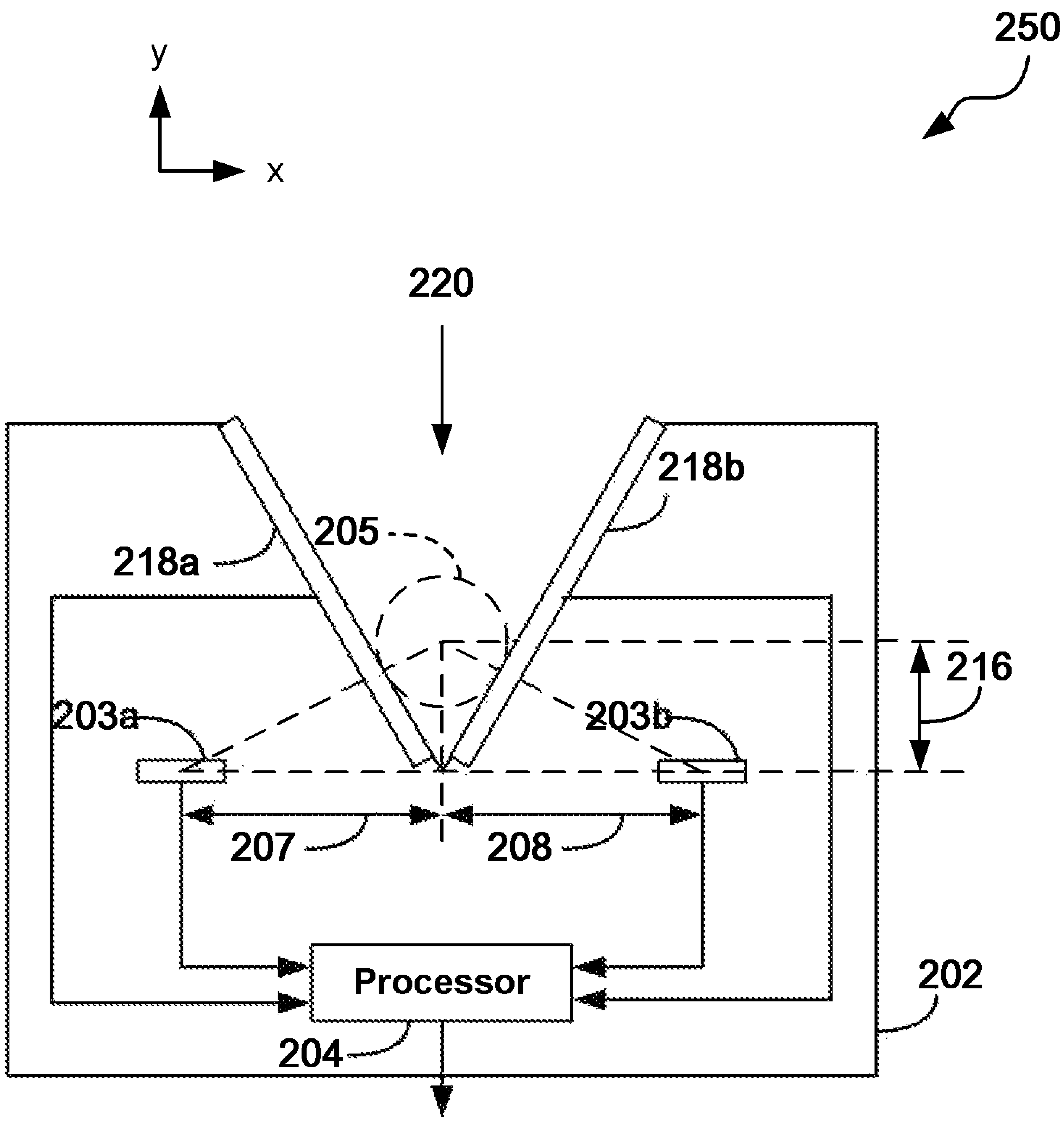

250
y
x
220
218b
205
218a
216
203a
203b
207
208
Processor
202
204

FIG. 2B

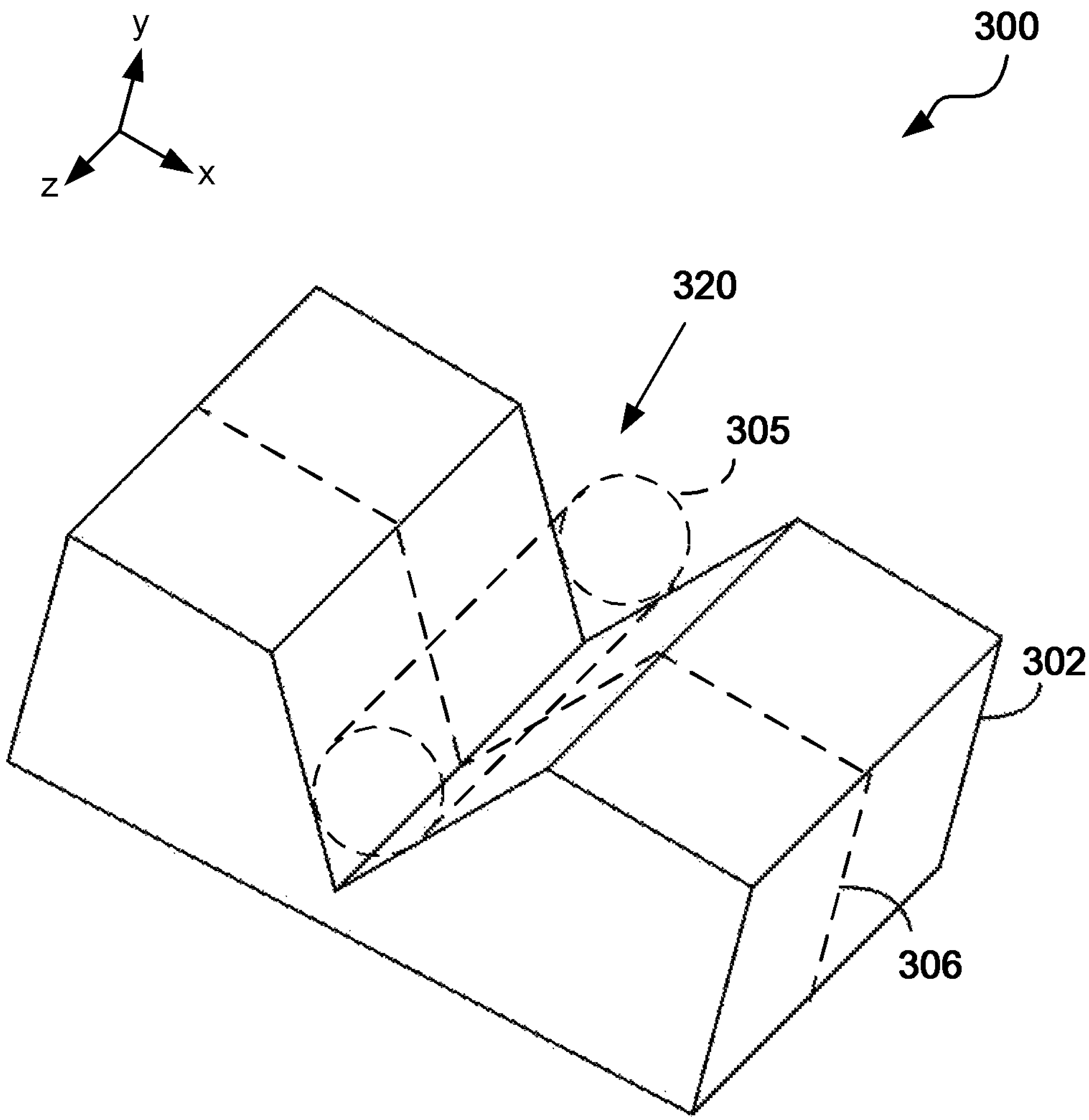



FIG. 3

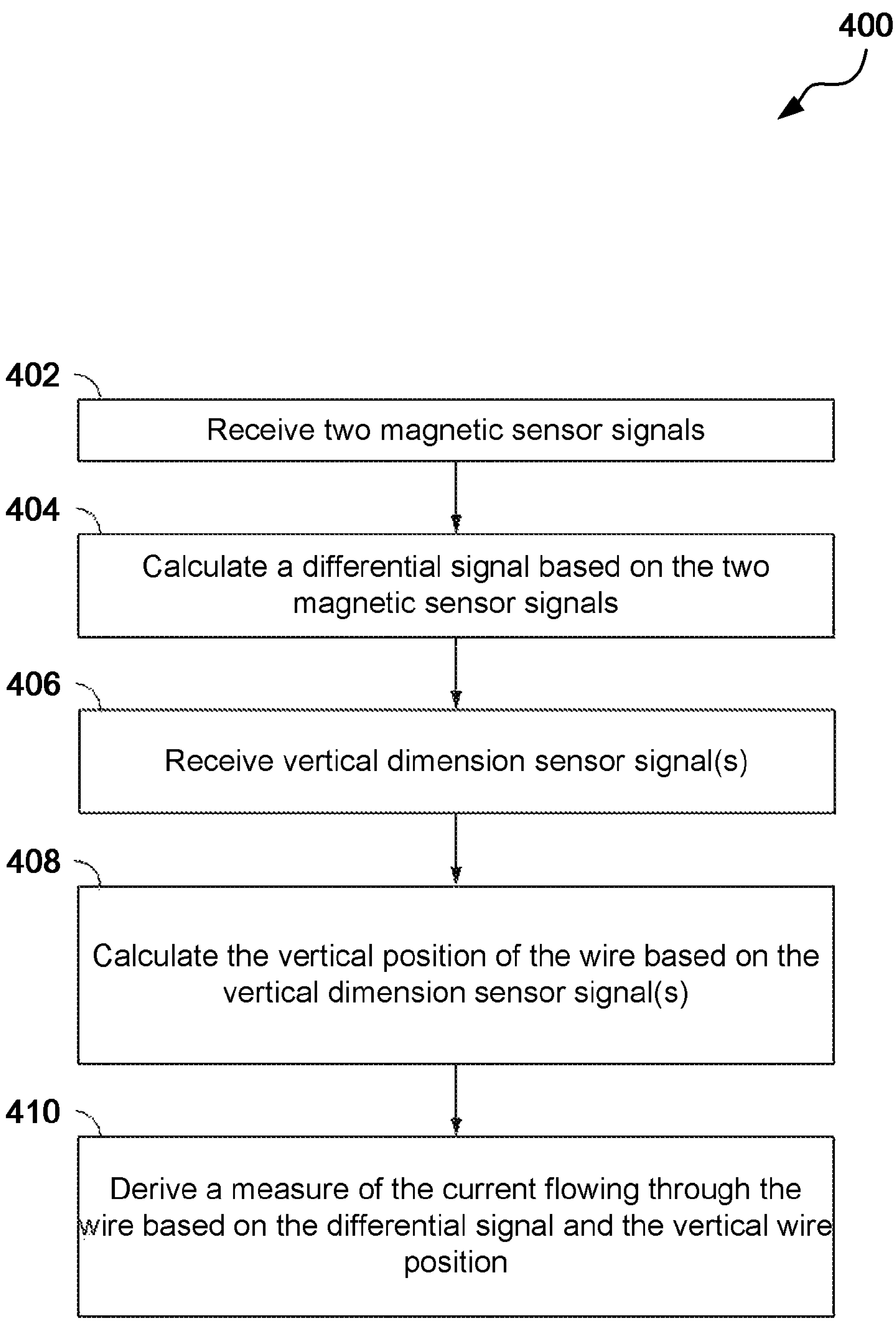

400
402
Receive two magnetic sensor signals
404
Calculate a differential signal based on the two magnetic sensor signals
406
Receive vertical dimension sensor signal(s)
408
Calculate the vertical position of the wire based on the vertical dimension sensor signal(s)
410
Derive a measure of the current flowing through the wire based on the differential signal and the vertical wire position

FIG. 4

# APPARATUS AND METHODS FOR MEASURING CURRENT

## BACKGROUND

Field

The described technology generally relates to measuring current and, more specifically, to apparatus and methods for sensing and/or measuring current flowing through a wire.

Description of the Related Art

Accurate measurement of current through a wire remotely (e.g., without breaking the wire or coming into contact with it) is useful for diagnostic, operational, and protection purposes in many applications, such as industrial and automotive applications. In particular, accurate current measurement without precise control of the placement of the wire may present various challenges. It can also be challenging to accurately measure current through the wire remotely when there are other current carrying wires located nearby, as the current flowing though such wires can interfere with the desired current measurement. One commonly used technique for alternating current (AC) measurements is using a Rogowski coil, which does not depend on the precise location of the wire inside the coil. However, Rogowski coils cannot make direct current (DC) measurements and can be too bulky for use in tight spaces.

## SUMMARY

The methods and devices of the described technology each has several aspects, no single one of which is solely responsible for its desirable attributes.

One embodiment includes an apparatus for measuring current flowing through a wire, and the apparatus comprises a housing with an opening configured to receive the wire and to define a location of a point of the wire in a first dimension when the wire is positioned in the opening, two magnetic sensors within the housing positioned on opposing sides of the opening in the first dimension, another one or more sensors, and a processor in communication with the two magnetic sensors and the another one or more sensors. The processor is configured to generate a differential signal indicative of a difference between outputs of the two magnetic sensors, determine a location of the point of the wire in a second dimension based on an output of the another one or more sensors, and derive a measure of the current flowing through the wire based on the differential signal and the determined location of the point of the wire in at least the second dimension.

Another embodiment includes an apparatus for measuring current flowing through a wire, and the apparatus comprises a body with an opening configured to receive and fix a horizontal position of the wire when the wire is positioned in the opening, two magnetic sensors positioned on opposing horizontal sides of the opening, at least one vertical position sensor configured to measure a vertical position of the wire when the wire is positioned in the opening, and a processor in communication with the two magnetic sensors and the at least one vertical position sensor, the processor configured to calculate a current flowing through the wire based on outputs of the two magnetic sensors and the at least one vertical position sensor.

Another embodiment includes a method for measuring current through a wire, and the method comprises generating a differential signal indicative of a difference between outputs of two magnetic sensors positioned on opposing sides of the wire in a first dimension, determining a location of a point of the wire in a second dimension based on an output of another one or more sensors, and deriving a measure of the current flowing through the wire based on the differential signal and the determined location of the point of the wire in the second dimension.



## BRIEF DESCRIPTION OF THE DRAWINGS

These drawings and the associated description herein are provided to illustrate specific embodiments of the described technology and are not intended to be limiting.

FIG. **1** is a block diagram illustrating an example current measurement system.

FIG. **2**A is a cross-sectional diagram illustrating an example apparatus for measuring current in accordance with one embodiment.

FIG. **2**B is a cross-sectional diagram illustrating an example apparatus for measuring current in accordance with another embodiment.

FIG. **3** is a three dimensional view of a portion of an example apparatus for measuring current in accordance with one embodiment.

FIG. **4** is a flowchart of an example process for measuring current in accordance with one embodiment.

## DETAILED DESCRIPTION

Various aspects of the novel systems, apparatuses, and methods are described more fully hereinafter with reference to the accompanying drawings. Aspects of this disclosure may, however, be embodied in many different forms and should not be construed as limited to any specific structure or function presented throughout this disclosure. Rather, these aspects are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the disclosure to those skilled in the art. Based on the teachings herein, one skilled in the art should appreciate that the scope of the disclosure is intended to cover any aspect of the novel systems, apparatuses, and methods disclosed herein, whether implemented independently of or combined with any other aspect. For example, an apparatus may be implemented or a method may be practiced using any number of the aspects set forth herein. In addition, the scope is intended to encompass such an apparatus or method which is practiced using other structure, functionality, or structure and functionality in addition to or other than the various aspects set forth herein. It should be understood that any aspect disclosed herein may be embodied by one or more elements of a claim.

Although particular aspects are described herein, many variations and permutations of these aspects fall within the scope of the disclosure. Although some benefits and advantages of the preferred aspects are mentioned, the scope of the disclosure is not intended to be limited to particular benefits, uses, or objectives. Rather, aspects of the disclosure are intended to be broadly applicable to different wired and wireless technologies, system configurations, networks, including optical networks, hard disks, and transmission protocols, some of which are illustrated by way of example in the figures and in the following description of the preferred aspects. The detailed description and drawings are merely illustrative of the disclosure rather than limiting, the scope of the disclosure being defined by the appended claims and equivalents thereof.

A current carrying wire generates a magnetic field in the orthogonal plane to the direction of current flow. A measurement of the magnetic field can be used to infer the magnitude of the current flowing in the wire. Hall Effect sensors can be used to measure magnetic fields using the Lorentz effect. Anisotropic magnetoresistive (AMR) sensors can measure the magnetic field based on the change in resistivity that is proportional to the perpendicular magnetic field. By using magnetic sensors, such as Hall Effect sensors and/or AMR sensors, certain challenges related to measuring current through a wire can be overcome according to aspects of this disclosure. For instance, embodiments described herein can overcome challenges related to the magnetic field interference from nearby current carrying wires. As another example, embodiments described herein can overcome challenges related to a location of the current carrying wire not being fixed. Since magnetic field strength should drop off inversely with distance from the current carrying wire, the distance from the wire can have a significant impact on inferring the current flowing through the wire using magnetic sensors. Furthermore, using certain magnetic sensors, such as Hall Effect and/or AMR sensors, apparatus disclosed herein can generate outputs that can be used to accurately make both alternating current (AC) and direct current (DC) measurements.

A body of an apparatus may include an opening that may deterministically locate a wire in at least a first dimension when the wire is placed in the opening. The apparatus may also include a plurality of sensors. At least one differential signal may be generated from signals from the magnetic sensors on opposing sides of the opening. Accordingly, common mode interference can be substantially canceled in the differential signal. Outputs of another one or more sensors can be used to determine the location of the wire in a second dimension. As such, the position of the wire within the opening can be precisely known in both the first dimension and the second dimension. The current flowing through the wire can be accurately derived from the at least one differential signal and the location of the wire in at least the second dimension.

Referring to FIG. **1**, a block diagram illustrating an example current measurement system will be described. The illustrated system includes a mobile current measuring apparatus **102**, having a current measuring unit **104**, memory **110**, a display **112**, and power source **114**. The current measuring unit **104** in turn may include sensors **106** and a processor **108**. The sensors **106** are configured to sense, for example, the differential magnetic field generated by current flowing through a wire. Embodiments of the current measuring unit **104** will be described in further detail in connection with FIGS. **2A-3** below. In some embodiments, some or all of the memory **110**, display **112**, and the power source **114** may reside in the same integrated unit as the sensors **106** and the processor **108**.

The memory **110** may be a non-transitory machine-readable storage medium such as a RAM, ROM, EEPROM, etc. The memory **110** may be in communication with the processor **108**, which may read from or write to the memory **110**. The display **112** may be configured to show the result of the current measurement performed in accordance with the disclosures herein. The display **112** may be any type of screen display, such as plasma display, liquid crystal display (LCD), organic light emitting diode (OLED) display, electroluminescent (EL) display, or any other indicator, such as a dial, barometer, or LEDs. In some implementations, the system may include a driver (not shown) for the display **112**. The power source **114** may provide power to substantially all components of the system of FIG. **1**. In some implementations, the power source **114** may be one or more battery units.

Referring to FIG. **2**A, a cross-sectional diagram illustrating an example apparatus for measuring current will be described. The illustrated apparatus **200** can implement the current measuring unit **104** (FIG. **1**). The illustrated apparatus **200** includes magnetic sensors **203***a*, **203***b*, and a processor **204**. The magnetic sensors **203***a*, **203***b*, and a processor **204** can implement the sensors **106** and the processor **108** of FIG. **1**, respectively. The apparatus **200** may also include a body **202**, and secondary or vertical position sensors **210**, **212**, which may be interchangeably referred to herein as secondary sensors or vertical position sensors. The sensors **106** of FIG. **1** can also include the secondary sensors **210**, **212**.

The body **202** may be a housing formed from one or more of various manufacturing processes, including injection molding and vacuum forming, for example. The body **202** may be made from one or more of various materials, including but not limited to plastic, glass, metal, ceramic, and rubber. The body **202** may include various colored or designed portions including different logos, symbols, marks, or pictures. The body **202** may include an opening **220** configured to receive a wire **205**. The wire **205** is typically not considered part of the apparatus **200**. The body **202** can provide a housing to encase the magnetic sensors **203***a*, **203***a*, the secondary sensors **210**, **212**, and the processor **204**. Accordingly, the apparatus **200** can be a relatively small integrated unit. The body **202** can include an output contact to provide an indication of current flowing through a wire.

The opening **220** may comprise a sloped recess that may contact the wire **205** at one or more contact points and/or surfaces when the wire **205** is positioned within the opening **220**. The illustrated opening **220** narrows as it extends into the body **202**. The opening **220** may be implemented to locate the wire **205** deterministically in at least one dimension when the wire **205** is firmly placed in the opening **220**. The wire **205**, for example, can be firmly placed in the opening **220** by a user pushing the wire **205** against the opening **220**. The opening **220** can be any suitable shape to deterministically define a position of the wire **205** in at least one dimension, such as a horizontal position. For instance, at least a portion of the opening **220** can be substantially V-shaped. As illustrated, the opening **220** may be a symmetric V-shaped jaw. Furthermore, the magnetic sensors **203***a*, **203***b* may be on the opposing sides of and approximately equidistance from the axis of symmetry of the V-shaped jaw so that respective distances **207** and **208** from the center point of the wire **205** to the magnetic sensors **203***a* and **203***b* may be approximately equal. In such embodiments, regardless of the thickness of the wire **205**, the center point of the wire **205** may be located approximately at the midpoint between the magnetic sensors **203***a* and **203***b* in a first dimension (e.g., the horizontal or x-dimension in FIG. **2**A). Depending on the thickness of the wire **205**, the location of the wire **205** in a second dimension (e.g., the vertical or y-dimension in FIG. **2**A) may not be the same for differently sized wires. Each wire **205** positioned within the opening **220** can have a fixed position in at least one dimension, even though the fixed position for a particular wire can be different than a fixed position for a differently dimensioned wire. The location of the wire **205** in a second dimension can be expressed as a vertical distance **216** between a point of the wire **205** (e.g., a center point) and the location of the magnetic sensors **203***a*, **203***b* in the second dimension. As illustrated, the second dimension can be orthogonal to the first dimension. It is to be noted that the horizontal and vertical dimensions or the x-, y-, and z-dimensions referred to herein denote orthogonal dimensions relative to one another and are not related to any absolute orientations, gravitational or otherwise. The vertical distance **216** may be determined with the processor **204** based on data from the secondary or vertical position sensors **210**, **212** in conjunction with data from the magnetic sensors **203***a*, **203***b* as further discussed below.

In some embodiments, the opening **220** may be a non-symmetric V-shaped jaw. In some other embodiments, the opening **220** may include a V-shaped portion and a non-V-shaped portion of the opening **220** may be curved or smoothened, for example, so that no acute angle or sharp edges may be present. In some other embodiments, the opening **220** may comprise a recess with a non-constant slope (e.g., concave up or down) to accommodate various widths of the wire **205**. Accordingly, the computation for deterministically locating the wire **205** may be modified from the disclosed implementations according to known or predetermined characteristics (e.g., shape, slope, curvature, symmetry, location or orientation relative to the sensors, etc.) of the opening **220**.

The opening **220** as described above can be advantageous for a current measuring apparatus in various ways. For instance, instead of having one or more mechanical moving parts to fasten the wire in a position, the opening **220** allows the user to simply push the wire **205** against the opening **220**. Not including a mechanical part to place the wire in position can be advantageous because inaccuracies resulting from moving parts can be eliminated and/or potential maintenance issues for the moving parts can be avoided. Moreover, implementing the current measurement system without moving parts can reduce costs relative to similar systems that include moving parts. Furthermore, the opening **220** with a widening structure as illustrated in FIGS. **2**A and **2**B allows the current measuring apparatus to accommodate for wires of various thicknesses, allowing the current measuring apparatus to be more adaptive and versatile. The forgoing descriptions of the opening **220** discuss only a few illustrative examples, and the opening **220** may be implemented in various ways that allow deterministic derivation of the location of the wire **205** in at least one dimension.

The magnetic sensors **203***a*, **203***b* may be magnetic sensors configured to detect the magnetic field around the wire **205**. The magnetic sensors **203***a*, **203***b* may be located on opposing sides of the opening **220** in the first dimension (e.g., the horizontal or x-dimension in FIGS. **2**A-**2**B). As such, the magnetic sensors **203***a*, **203***b* will be on opposing sides of a wire **205** positioned within the opening **220**. In some embodiments the magnetic sensors **203***a*, **203***b* may be magnetoresistive (MR) sensors, such as anisotropic magnetoresistive (AMR) sensors, or Hall Effect sensors. AMR sensors can be relatively small compared to other types of magnetic sensors, such as Rogowski coils. Accordingly, AMR sensors can be used in relatively small current sensing equipment, which can make measurements in hard to reach areas. The magnetic sensors **203***a*, **203***b* may comprise magneto-resistive materials whose electrical resistance varies according to an external magnetic field. In some embodiments, the magnetic sensors **203***a*, **203***b* may be positioned in the orientation that would allow detecting the magnetic field in a plane orthogonal to the direction of current flowing through the wire **205**. The magnetic sensors **203***a*, **203***b* may be configured to generate measurement signals and send the signals to the processor **204**. Processing of the signals from the magnetic sensors **203***a*, **203***b* will be discussed further below.

The secondary sensors **210**, **212** may be configured to detect the magnetic field around the wire **205** to determine the location of the wire **205** in the second dimension (e.g., the vertical or y-dimension in FIG. **2**A). The secondary sensors **210**, **212** and the magnetic sensors **203***a*, **203***b* may be located on the opposing sides of the wire **205** to be received in the opening **220** in the second dimension. The secondary sensor **210** and the secondary sensor **212** may also be located on the opposing sides of the opening **220** in the first dimension such that the secondary sensors **210** and **212** are on opposing sides of a wire **205** positioned within the opening **220**. In some embodiments, the first magnetic sensor **203***a* and the first secondary sensor **210** can be on an opposite sides of the opening **220** in the first dimension than the second magnetic sensor **203***b* and the second secondary sensor **212**. Such an arrangement may be advantageous for canceling out common interference measured by the sensor pairs as further described below. As illustrated, the first magnetic sensor **203***a* and the first secondary sensor **210** can be aligned along the second dimension. In some embodiments, both the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212** can be MR sensors, such as AMR sensors. When the magnetic sensors **203***a*, **203***b* are AMR sensors, implementing the secondary sensors **210**, **212** as AMR sensors can be relatively inexpensive. Furthermore, AMR sensors can be relatively small and an integrated unit with the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212** as AMR sensors within the body **202** can be relatively compact. Such a relatively compact integrated unit can be measure current flowing through a wire when a wire is located in a small or difficult to reach place. In some embodiments, the secondary sensors **210**, **212** may be positioned in the orientation that detects the magnetic field in a plane orthogonal to the direction of the current flowing through the wire **205**. Signals generated by the secondary sensors **210**, **212** may be communicated to the processor **204** to determine the position of the wire **205** in the second dimension, which will be discussed further below.

The processor **204** may be in communication with the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212**. The processor **204** can derive a measure of current flowing through the wire **205** positioned in the opening **220**. The processor **204** can derive the measure of current flowing through the wire **205** based on outputs of the magnetic sensors **203***a*, **203***b*, and the secondary sensors **210**, **212**. For instance, the processor **204** can derive a measure of current flowing through the wire **205** based on a differential signal generated from the outputs of the magnetic sensors **203***a*, **203***b* and a location (e.g., the y-dimension location) of a point (e.g., center) of the wire **205** determined based on signals from the secondary or vertical position sensors **210**, **212**. In another example, the processor **204** can determine a distance between at least one of the magnetic sensors **203***a*, **203***b* and the point of the wire **205** to derive the measure of the current flowing through the wire **205**. In some instances, the processor **204** can derive the measure of current flowing through the wire **205** based on calculated distances from at least two of the magnetic sensors **203***a*, **203***b*, and the secondary sensors **210**, **212**.

The processor **204** may be configured to receive measurement signals from the magnetic sensors **203***a*, **203***b* to generate a differential signal. Each of the signals from the magnetic sensors **203***a*, **203***b* may include interference from the environment, such interference from magnetic fields generated by other wires nearby. Since the magnetic sensors **203***a*, **203***b* may be located relatively near to each other on the opposing sides of the wire **205**, apart from each other by approximately the maximum thickness of a wire the body **202** is configured to receive, the interference included in each of the signals from the magnetic sensors **203***a*, **203***b* may be approximately equal to each other. This common mode interference in the signals from the magnetic sensors **203***a*, **203***b* may be cancelled out by generating the differential signal from a difference between the two signals from the magnetic sensors **203***a*, **203***b*. In an embodiment in which the distances **207** and **208** are approximately equal to each other, the differential signal from the magnetic sensors **203***a*, **203***b* in conjunction with data from the secondary sensors **210**, **212** may be used to determine the current flowing through the wire **205** without expressly calculating the location of the wire in the first dimension (e.g., the horizontal or x-dimension in FIG. **2**A).

For example, when the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212** are AMR sensors, the magnetic field measurements from the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212** may be expressed in terms of the location of the center of the wire in the second dimension and the current flowing through the wire based on the relationship between the magnetic flux intensity and the current flowing through the wire **205** and the anisotropic characteristics of the magnetic sensors **203***a*, **203***b*, and the secondary sensors **210**, **212** in some implementations. In general, magnetic flux intensity may be expressed as follows:

$$H = \frac{I}{2\pi r} \quad \text{(Equation 1)}$$

where H is magnetic flux intensity, I is current flowing through a wire (e.g., the wire **205**), and r is the distance between the center of the wire and a sensor (e.g., the center of the wire **205** and one of the sensors **203***a*, **203***b*, **210**, **212**) assuming that the wire is infinitely long in the z-dimension (coming out of the page in FIG. **2**A, for example). The infinitely long wire assumption may provide a reasonable approximation when the wire **205** is straight without bending in the z-dimension for at least about **10** times the distance between the sensors, for example. When the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212** are implemented with anisotropic sensors, the sensors **203***a*, **203***b*, **210**, **212** may be positioned so that only the proportion of the magnetic flux intensity in the second dimension (e.g., the y-dimension in FIG. **2**A) may be sensed. The magnetic sensors **203***a*, **203***b* can be oriented so that they are sensitive to opposite directions, and the secondary sensors **210**, **212** may be oriented so that they are sensitive to opposite directions both in the second dimension (e.g., the y-dimension in FIG. **2**A). In this implementation, the differential signals from the sensors **203***a*, **203***b*, **210**, **212** would sum the magnetic flux components in the second dimension (e.g., the y-dimension in FIG. **2**A), and the magnetic flux intensity for one sensor may be expressed as follows:

$$H = \frac{I}{2\pi r}\cos\phi \quad \text{(Equation 2)}$$

where Φ is the angle between the direction of the flux intensity and the critical direction (i.e., the direction in which the anisotropic sensor is sensitive to) of the sensor (e.g., the sensors **203***a*, **203***b*, **210**, **212**). Since the direction of the magnetic flux is perpendicular to the radial distance r from the wire to the sensor (e.g., the center of the wire **205** and one of the sensors **203***a*, **203***b*, **210**, **212**), and the critical direction is in the second dimension (e.g., the y-dimension in FIG. **2**A), cos Φ may be expressed as

$$\frac{a}{r}$$

where a is the first dimension distance between one of the sensors and the wire (e.g., the distance **207** or **208**). Therefore, substituting

$$\frac{a}{r}$$

for cos Φ in Equation 2, the differential signal from the magnetic sensor pairs (e.g., **203***a* and **203***b*, or **210** and **212**) can be expressed in general as below:

$$H = \frac{Ia}{2\pi r^2} + \frac{Ia}{2\pi r^2} = \frac{Ia}{\pi r^2} \quad \text{(Equation 3)}$$

Using the Pythagorean theorem to substitute $r^2$, the differential signals from the magnetic sensors **203***a* and **203***b* can be expressed as below:

$$H_1 = \frac{Ia}{\pi(a^2 + b^2)} \quad \text{(Equation 4)}$$

where $H_1$ is the differential signal from the magnetic sensors **203***a*, **203***b* and b is the second dimension distance between the sensors and the wire (e.g., the distance **216**). Similarly, the differential signal from the secondary sensors **210**, **212** may be expressed as below:

$$H_2 = \frac{Ia}{\pi(a^2 + (c-b)^2)} \quad \text{(Equation 5)}$$

where $H_2$ is the differential signal from the secondary sensors **210**, **212**, and c is the second dimension distance between the sensors (e.g., the distance **214**). Based on the obtained differential sensor data corresponding the magnetic flux intensities (i.e., $H_1$ and $H_2$) and a priori knowledge of the distances a (e.g., **207** or **208**) and c (e.g., **214**), Equations 4 and 5 may be solved for the distance b (e.g., **216**) and the current I through the wire (e.g., **205**). The distances a and c can be known from the placement of the sensors **203***a*, **203***b*, **210**, and **212**. As noted above, b can vary depending on a particular wire **205** placed in the opening **220**. Thus, one way of accurately measuring current flowing through a wire **205** positioned in the opening **220** that can account for varying placements of a center point of different wires in the vertical dimension shown in FIG. **2**A has been provided.

According to some other implementations, when the distances **207** and **208** are not approximately equal to each other, the difference in these distances can be accounted for by applying an adjustment, such as a scale factor, to a signal generated by at least one of the magnetic sensors **203***a*, **203***b*. In an embodiment in which the distances **207** and **208** are not approximately equal to each other, the location of a selected point of the wire **205** in both dimensions may be determined based on data from the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212**.

The processor **204** may be further configured to receive measurement signals from the secondary sensors **210**, **212**. The secondary sensors **210**, **212** may also generate outputs that include interference from the surrounding environment, and the interference may be cancelled out by taking the difference between the signals from the secondary sensors **210**, **212**. Furthermore, since the magnetic field around a current-carrying wire drops off inversely with distance, the location of the wire **205** in the second dimension (e.g., the vertical or y-dimension in FIG. 2A) may be determined based on the differential signals from the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212**. The processor **204** may be configured to compare the differential signal from the magnetic sensors **203***a*, **203***b* and the differential signal from the sensors **210**, **212** to determine the location of the wire **205** in the second dimension. For example, in an embodiment in which the distances **207** and **208** are approximately equal to each other, the distance **216** can be computed by solving Equations 4 and 5 as discussed above. In another embodiment in which the distances **207** and **208** are not approximately equal to each other, the distance **216** can be computed based on the equations below:

$$a'=a_1+a_2 \quad \text{(Equation 6)}$$

$$H_1=\frac{Ia_1}{2\pi r_1^2}+\frac{Ia_2}{2\pi r_2^2}=\frac{Ia_1}{2\pi(a_1^2+b^2)}+\frac{Ia_2}{2\pi(a_2^2+b^2)} \quad \text{(Equation 7)}$$

$$H_2=\frac{Ia_1}{2\pi r_3^2}+\frac{Ia_2}{2\pi r_4^2}=\frac{Ia_1}{2\pi(a_1^2+(c-b)^2)}+\frac{Ia_2}{2\pi(a_2^2+(c-b)^2)} \quad \text{(Equation 8)}$$

where a' is the first dimension (e.g., x-dimension) distance between the sensor pairs (**203***a*, **203***b*) and (**210**, **212**), $a_1$ is the first dimension distance between the wire and the first magnetic sensor (e.g., the distance **207**), $a_2$ is the first dimension distance between the wire and the second magnetic sensor (e.g., the distance **208**), and $r_1$, $r_2$, $r_3$, and $r_4$ are the radial distances between the wire and the four sensors **203***a*, **203***b*, **210**, and **212**, respectively. Similar to the previous example in connection with Equations 4 and 5, from the placement of the sensors **203***a*, **203***b*, **210**, and **212**, the distances a', $a_1$, $a_2$, and c can be known, and two unknowns (the distance b (e.g., **216**) and the current I through the wire (e.g., **205**)) can be solved using two equations.

The processor **204** may be configured to determine the current flowing through the wire **205** based on the differential signal from the magnetic sensors **203***a*, **203***b* and the position of the wire in the second dimension, for example. The current flowing through the wire **205** can be determined based on Equations 1-8 discussed above. Therefore, the processor **204** may derive the current flowing through the wire **205** from the sensor data.

Referring to FIG. 2B, a cross-sectional diagram illustrating another example apparatus for measuring current will be described. The illustrated apparatus **250** may implement the current measuring unit **104** (FIG. **1**). The apparatus **250** is substantially the same as the apparatus **200** (FIG. 2A) except that the secondary or vertical position sensors **210**, **212** are replaced by secondary or vertical position sensing elements **218***a*, **218***b*, respectively.

The secondary sensing elements **218***a*, **218***b* may be configured to detect the location of the wire **205** positioned within the opening **220** in a second dimension (e.g., the vertical or y-dimension in FIG. 2B). The sensing elements **218***a*, **218***b* may be located along the walls of the opening **220** as illustrated in FIG. 2B. The secondary sensing elements **218***a*, **218***b* may be an infrared (IR) light emitting diode (LED) sensor set. Accordingly, the secondary sensing elements **218***a*, **218***b* can together be considered a single sensor. For example, one of the secondary sensing elements **218***a* may be an emitter of an IR LED sensor, and the other of the secondary sensing elements **218***b* may be a detector of the IR LED sensor, or vice versa. The secondary sensing elements **218***a*, **218***b* may also be tactile sensors. The secondary sensors **210**, **212** (FIG. 2A) and/or the secondary sensing elements **218***a*, **218***b* may be implemented by any type of sensor(s) suitable to provide signals to the processor **204** from which a position of the wire **205** within the opening **220** in a dimension other than the first dimension can be determined by the processor **204**.

The processor **204** may be in communication with the magnetic sensors **203***a*, **203***b* and the secondary sensing elements **218***a*, **218***b*. The signals from the magnetic sensors **203***a*, **203***b* may be processed by the processor **204** as discussed above in connection with FIG. 2A. The secondary sensing elements **218***a*, **218***b* may detect presence of the wire **205** at a portion of the wall along the opening **220**. For example, the secondary sensing elements **218***a*, **218***b* may detect that in some part of the wall of the opening **220**, the IR LED signal emitted from the emitter (e.g., **218***b*) is not detected by the detector (e.g., **218***a*). In another example, the secondary sensing elements **218***a*, **218***b* may detect that the wire **205** is in contact with one or both of the secondary sensing elements **218***a*, **218***b* at a certain point along the wall of the opening **220**. The processor **204** may be configured to determine the location of a selected point of the wire **205** (e.g., the center point) based on the signals from the secondary sensing elements **218***a*, **218***b* indicating the presence and location of the wire **205** within the opening. The location of the wire **205** may be expressed as the distance between the magnetic sensors **203***a*, **203***b* and the center of the wire **205** in the second dimension (e.g., the y-dimension in FIG. 2B). The differential signal from the magnetic sensors **203***a*, **203***b* in conjunction with the location of the wire **205** in the second dimension may be used to derive the current through the wire **205** as discussed in above.

Referring to FIG. **3**, a three dimensional view of a portion of an example apparatus for measuring current will be described. The illustrated portion of the apparatus **300** includes a body **302** with an opening **320**, which may receive a wire **305** and a cross-sectional plane **306**. The wire **305** is not typically considered part of the apparatus **300**. The body **302** and the opening **320** can implement any combination of features of the body **202** and the opening **220**, respectively, of FIGS. 2A-2B. Although not shown, other elements, including the sensors and the processor, illustrated in FIGS. 2A-2B may be included in the apparatus **300**, in some embodiments within the body **302**. The illustrations in FIGS. 2A-2B may be along the cross-sectional plane **306**, and the magnetic sensors **203***a*, **203***b* and the secondary sensors **210**, **212**, **218***a*, **218***b* of FIGS. 2A-2B may be located on the cross-sectional plane **306**. Accordingly, firmly placing the wire **305** by pressing against the opening **320** at around the cross-sectional plane **306** may be advantageous for accurate current measurement.

Referring to FIG. **4**, a flowchart of an example process for measuring current will be described. The process **400** may be performed by, for example, the processor **108** (FIG. **1**) and/or the processor **204** (FIGS. 2A and/or 2B). The process **400** may be implemented by the processor **108** and/or **204** in some embodiments. Some or all of the process **400** may be stored in a non-transitory computer-executable form in the memory **110**, for example.

At block **402**, sensor signals from two magnetic sensors may be received. The two magnetic sensors, such as the magnetic sensors **203***a*, **203***b* in FIGS. **2**A-**2**B, may detect changes in resistance due to the magnetic field generated around the wire carrying current and generate sensor signals. The processor **204** (FIGS. **2**A-**2**B) may receive these signals for further processing.

At block **404**, a differential signal based on the two received sensor signals may be calculated. In some embodiments, the differential signal may be a simple difference between the two received sensor signals. As discussed in connection with FIG. **2**A, the processor **204** may remove almost all common mode interference from the signals from the magnetic sensors **203***a*, **203***b* by calculating the differential signal from the received magnetic sensor signals from the magnetic sensors **203***a*, **203***b*.

At block **406**, one or more vertical dimension sensor signals may be received. The processor **204** (FIGS. **2**A-**2**B) may obtain the one or more vertical dimension sensor signals from the secondary sensors **210**, **212** in FIG. **2**A or the secondary sensors **218***a*, **218***b* in FIG. **2**B.

At block **408**, the vertical position of the wire may be determined based at least in part on the secondary sensor signals. In one embodiment, the processor **204** (FIG. **2**A) may determine the position of the wire in the second dimension (e.g., the vertical or y-dimension in FIG. **2**A) by comparing the differential signal from the magnetic sensors **203***a*, **203***b* and the differential signal from the secondary sensors **210**, **212** as discussed in connection with FIG. **2**A. In another embodiment, the processor **204** (FIG. **2**B) may determine the position of the wire in the second dimension (e.g., the vertical or y-dimension in FIG. **2**B) by determining the vertical location of the wire from the signals from the secondary sensors **218***a*, **218***b* as discussed in connection with FIG. **2**B.

At block **410**, the current through the wire may be determined based on the differential signal of the first sensor set and the vertical position of the wire. The processor may derive the current through the wire from the differential signal from the magnetic sensors **203***a*, **203***b* and the position of the wire in the second dimension (e.g., the vertical or y-dimension in FIGS. **2**A-**2**B) determined at the previous block. This can involve performing one or more computations discussed above.

The foregoing description and claims may refer to elements or features as being "connected" or "coupled" together. As used herein, unless expressly stated otherwise, "connected" means that one element/feature is directly or indirectly connected to another element/feature, and not necessarily mechanically. Likewise, unless expressly stated otherwise, "coupled" means that one element/feature is directly or indirectly coupled to another element/feature, and not necessarily mechanically. Thus, although the various schematics shown in the Figures depict example arrangements of elements and components, additional intervening elements, devices, features, or components may be present in an actual embodiment (assuming that the functionality of the depicted circuits is not adversely affected).

As used herein, the term "determining" encompasses a wide variety of actions. For example, "determining" may include calculating, computing, processing, deriving, investigating, looking up (e.g., looking up in a table, a database or another data structure), ascertaining and the like. Also, "determining" may include receiving (e.g., receiving information), accessing (e.g., accessing data in a memory) and the like. Also, "determining" may include resolving, selecting, choosing, establishing and the like. Further, a "channel width" as used herein may encompass or may also be referred to as a bandwidth in certain aspects.



The various operations of methods described above may be performed by any suitable means capable of performing the operations, such as various hardware and/or software component(s), circuits, and/or module(s). Generally, any operations illustrated in the Figures may be performed by corresponding functional means capable of performing the operations.

The various illustrative logical blocks, modules, and circuits described in connection with the present disclosure may be implemented or performed with a general purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array signal (FPGA) or other programmable logic device (PLD), discrete gate or transistor logic, discrete hardware components or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any commercially available processor, controller, microcontroller or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

The methods disclosed herein comprise one or more steps or actions for achieving the described method. The method steps and/or actions may be interchanged with one another without departing from the scope of the claims. In other words, unless a specific order of steps or actions is specified, the order and/or use of specific steps and/or actions may be modified without departing from the scope of the claims.

Applications

It is to be understood that the implementations are not limited to the precise configuration and components illustrated above. Various modifications, changes and variations may be made in the arrangement, operation and details of the methods and apparatus described above without departing from the scope of the implementations.

Although this invention has been described in terms of certain embodiments, other embodiments that are apparent to those of ordinary skill in the art, including embodiments that do not provide all of the features and advantages set forth herein, are also within the scope of this invention. Moreover, the various embodiments described above can be combined to provide further embodiments. In addition, certain features shown in the context of one embodiment can be incorporated into other embodiments as well.

What is claimed is:

**1**. An apparatus for measuring current flowing through a wire, the apparatus comprising:

a housing with an opening comprising a sloped recess, wherein the opening is configured to receive the wire in a direction substantially in a dimension;

two magnetic sensors within the housing;

another one or more sensors; and

a processor in communication with the two magnetic sensors and the another one or more sensors, the processor configured to derive a measure of the current flowing through the wire based on outputs of the two magnetic sensors and a determined location of the point of the wire in the dimension, the determined location being based on an output of the another one or more sensors.

2. The apparatus of claim 1, wherein the dimension is a second dimension, and wherein the opening has a shape that defines a location of a point of the wire in a first dimension when the wire is positioned in the opening.

3. The apparatus of claim 2, wherein the opening is configured to define the same location of a center point of the wire in the first dimension independent of the width of the wire.

4. The apparatus of claim 2, wherein the point of the wire is a center point of the wire, and wherein the two magnetic sensors are approximately equal distance from the center point of the wire in the first dimension.

5. The apparatus of claim 2, wherein the processor is configured to:

determine a distance between the point of the wire and at least one of the two magnetic sensors based on the defined location of the point of the wire in the first dimension and the determined location of the point of the wire in the second dimension;

wherein the processor is configured to derive the measure of the current based on the determined distance.

6. The apparatus of claim 2, wherein the two magnetic sensors are positioned on opposing sides of the opening in the first dimension.

7. The apparatus of claim 1, wherein at least a portion of the opening is substantially V-shaped.

8. The apparatus of claim 1, wherein the dimension is a second dimension, and wherein the two magnetic sensors are disposed in a plane along a first dimension.

9. The apparatus of claim 1, wherein the processor is configured to:

determine an alternating current (AC) measure of current flowing through the wire; and

determine a direct current (DC) measure of current flowing through the wire.

10. The apparatus of claim 1, wherein the two magnetic sensors are anisotropic magnetoresistance (AMR) sensors.

11. The apparatus of claim 10, wherein the another one or more sensors comprise anisotropic magnetoresistance (AMR) sensors positioned on an opposite side of a plane perpendicular to the current through the wire than the two magnetic sensors.

12. The apparatus of claim 1, wherein at least one of the processor or the additional one or more sensors are within the housing.

13. The apparatus of claim 12, wherein the housing comprises a contact configured to output the measure of current flowing through the wire.

14. The apparatus of claim 1, wherein the processor is further configured to generate a differential signal indicative of a difference between the outputs of the two magnetic sensors, and wherein the measure of the current is based on the differential signal and the determined location of the point of the wire in the second dimension.

15. The apparatus of claim 1, wherein the opening is configured such that a length of the wire extends along a different dimension than the dimension when the wire is positioned in the opening.

16. A method for measuring current through a wire, the method comprising:

receiving outputs of two magnetic sensors

determining a location of a point of the wire in a dimension based on an output of another one or more sensors, wherein the wire is positioned in an opening such that a length of the wire extends along a different dimension than the dimension, and wherein the opening is configured to receive the wire in a direction substantially in the dimension; and

deriving a measure of the current flowing through the wire based on the outputs of the two magnetic sensors and the determined location of the point of the wire in the dimension.

17. The method of claim 16, wherein the dimension is a second dimension, and wherein the opening defines a location of the wire in a first dimension.

18. The method of claim 16, wherein the point of the wire is a center point, wherein the dimension is a second dimension, and wherein the two magnetic sensors are approximately equal distance from the center point of the wire in a first dimension.

19. The method of claim 16, wherein the deriving the measure of the current through the wire comprises deriving a direct current (DC) measure.

20. The method of claim 17, wherein the deriving includes determining distances between the point of the wire and the two magnetic sensors based on the defined location of the point of the wire in the first dimension and the determined location of the point of the wire in the second dimension.

21. The method of claim 16, wherein the opening comprises a sloped recess.

22. The method of claim 16, further comprising generating a differential signal indicative of a difference between the outputs of the two magnetic sensors, wherein the deriving is based on the differential signal and the determined location of the point of the wire.

23. An apparatus for measuring current flowing through a wire, the apparatus comprising:

a body with a recess configured to receive and fix a horizontal position of the wire when the wire is positioned in the recess;

two magnetic sensors positioned on opposing horizontal sides of the recess;

at least one vertical position sensor configured to measure a vertical position of the wire when the wire is positioned in the recess; and

a processor in communication with the two magnetic sensors and the at least one vertical position sensor, the processor configured to calculate a current flowing through the wire based on outputs of the two magnetic sensors and the at least one vertical position sensor.

24. An apparatus for measuring current flowing through a wire, the apparatus comprising:

a housing with an opening configured to receive the wire and to define a location of a point of the wire in a first dimension when the wire is positioned in the opening, wherein the opening comprises a recess;

two magnetic sensors within the housing positioned on opposing sides of the opening in the first dimension;

another one or more sensors; and

a processor in communication with the two magnetic sensors and the another one or more sensors, the processor configured to:

generate a differential signal indicative of a difference between outputs of the two magnetic sensors;

determine a location of the point of the wire in a second dimension based on an output of the another one or more sensors; and

derive a measure of the current flowing through the wire based on the differential signal and the determined location of the point of the wire in at least the second dimension.

**25**. The apparatus of claim **24**, wherein the opening is arranged to receive the wire from a direction substantially in the second dimension.

* * * * *